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Microscopic and Macroscopic Fluid Distribution Experiments

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SUMMARY

The ultimate objectives of project BE12B are to study and characterize, on both macroscopic and microscopic scales, the two-phase fluid distribution and the effect of heterogeneities associated with a rock-composition/pore-system type and to correlate the results with the observed heterogeneities. To achieve this objective, the scope of the work was divided into six tasks as outlined in the Annual Research Plan for FY88. These tasks are: (1) selection of a rock/fluid system and development of experimental equipment; (2) set up videomicroscopy equipment; (3) perform displacement experiments in the rock sample; (4) design, fabricate, and perform experiments in micromodels; (5) study thin sections; and (6) analyze the results and explane the flow behavior.

This report describes the work accomplished in tasks 1 through 4. The work required to accomplish tasks 1, 2, 3, and 4 has been divided into the following five steps:

1. Selection of a rock-fluid system which would enhance frontal instabilities when displacement is carried out under typical reservoir conditions, and allow pore-level visual observations of fluid distribution.

2. Development of a strategy to construct three-dimensional fluid front profiles and use the results to select appropriate thin slabs of the rock to study the role of fluid heterogeneities on distribution at the pore level.

3. Selection of or improvement of an existing micromodel fabrication technique; or development of a better technique for making more realistic micromodels.

4. Selection of an appropriate photomicroscopy system capable of capturing images of both static and dynamic pore level behavior, under low-contrast and low-light conditions.

5. Continuation of modification of the nuclear magnetic resonance (NMR) spectrometer for its transformation to an NMR imager. If a successful transformation is obtained, this apparatus will also be used to study fluid distribution in core samples at the pore level.

This report presents a summary of the technical progress in these five areas.

DISCUSSION OF TECHNICAL PROGRESS

Characterizing Frontal Behavior

Berea sandstone and Teapot Dome subsurface core plugs were selected for this study. These high-permeability, high-porosity, and relatively clean cores were selected to aid in fluid visualization. In low-porosity thin slices of rock, only one or two pores can be seen at 100X magnification in one frame, which is not desirable for a comparative study. Clean cores were needed because the presence of argillaceous materials reduced the light transmission through thin slices of rock. Relatively homogeneous rocks were selected to avoid channeling.

Displacement studies are being performed on Berea sandstone cores. The initial displacement tests consisted of saturating the cores with 1% NaCl brine and displacing the brine with Soltrol-220, which has a viscosity of approximately 5 cP. The oil injection was stopped soon after oil broke through. From these experiments, it was found that instability did not occur even at high oil rates.

Instability of the fluid front movement is required for frontal behavior characterization. The first attempt to induce instability was to add glycerin to the brine to increase its viscosity to 80 cP, but this procedure resulted in some operational problems. During the injection of the 80-cP brine, the core sleeve broke, and we reduced the viscosity of the brine to 40 cP.

The test core was saturated with this lower viscosity glycerated brine and displaced by Soltrol-200 until oil breakthrough. The core was then CT-scanned in both areal and transverse directions of flow within 2 to 3 hours of stopping the test. The results once again showed that there was no indication of fingering when the CT scan was taken. A possible explanation for this behavior might have been the redistribution of the fluids before the CT scan.

The experimental procedure was revised, and the displacement apparatus was redesigned so that experiments could be performed in the CT room. Great safety precautions were required because a medical CT apparatus is being used in this study. The same procedure as that previously described was followed, and the results indicated that oil displaced brine preferentially from the periphery of the core. The reasons for this behavior are not understood. It is speculated that the epoxy wrapping on the core and/or the inlet end cap caused this anomalous behavior. The experimental procedure has once more been revised. The new procedure involves Peter's and Flock's[1] criterion for viscous fingering to estimate critical velocity. Gas is now used as the displacing phase.

Front Profile Construction and Mapping

The following strategy for mapping fluid flow has been developed. Immediately after displacement is stopped (after oil breakthrough), the entire length of the cores will be CT scanned, both in the normal and transverse directions. The cores will then be cut into thin slices and will be preserved in Soltrol-220. The pockets of high fluid saturations as seen by CT scans will be mapped on corresponding thin slices of rock, and the characteristics of each zone of interest will be visualized and captured (at static conditions), for statistical analysis using the commercially available image analysis software programs. Fluid flow behavior, fluid distribution, and pore topology for each thin slice of rock will be analyzed simultaneously. Preliminary conclusions will be drawn regarding the role of micro-heterogeneities in pore structure on two-phase flow behavior.

Micromodel Fabrication

The most important step in determining the effects of pore structure on oil (or contaminants) ganglia movement is to select, improve, or develop a suitable technique for encapsulating thin slices of rock for flow studies or make an exact replica of the pore structure using transparent materials for dynamic studies. An inherent problem is the poor light transmission for visualization. The commonly used fabrication techniques result in either too unrealistic pore structures or suffer from operational problems, such as flowthrough discontinuities at the surfaces or ends which almost always overwhelm the flow behavior. Existing techniques were outlined after a comprehensive literature search, and the promising ones were evaluated.

The literature search showed that the most common micromodels used during flow studies are sandpack, cryolite, and etched glass. Even though these three micromodels represent porous media to a certain extent, it is clear that many features which exist in porous media are not present in these micromodels. This evaluation indicated that the techniques for using micromodels should be reevaluated. Two novel techniques, thin slab and pore cast, have been proposed for investigation.

A micromodel was fabricated containing a thin slab of rock (2 mm thick). Flow visualization through this slab was accomplished with the videomicroscopy equipment described below. We are working to improve the contrast by using better dyes and filters. The results from the use of dyes are presented in the next section.

The fabrication of pore cast micromodels from Berea sandstone thin slabs has also been partially successful. The oil-wet characteristic of the pore cast has generated some challenging work. Several chemicals are being used to change the wettability from oil-wet to water-wet.

Fluid flow studies using micromodels containing a thin slab of rock will indicate true fluid flow behavior at the microscopic scale. We decided that other types of micromodels should also be fabricated for future studies.

The methodologies for the fabrication of each of these micromodels were determined, and at least one micromodel of each type (etched glass, cryolite, and sandpack) has been fabricated successfully. More micromodels of these types are being fabricated with different scale sizes to determine the role of pore dimensions on flow behavior.

Videomicroscopic Equipment

The essence of this task was to set up a microscopy system capable of capturing low-light, high-speed events during fluid flow through micromodels with a high contrast and high resolution. Many sophisticated systems were tried, but most of them have severe limitations. We decided, therefore, to acquire several specific systems instead of a single multipurpose system. After experimenting with many options, the following plan of work was developed:

(a) modify the fluorescence microscope for a more powerful light source (300 watts quartz halogen tungsten);

(b) illuminate simultaneously with epifluorescent blue light and green filter;

(c) capture the image using a high-sensitivity, high-resolution and high-contrast black and white video camera for static fluid distribution;

(d) use a motion picture camera (6000 fps, 16 mm film) to capture dynamic behavior;

(e) use an image analysis package to enhance and color (pseudo) the images; and

(f) use a low-resolution, color, video camera to record the movement in true color.

Assembly and testing of the videomicroscopic equipment were completed successfully this quarter. The high-resolution, high-contrast, high-sensitivity, black and white video camera (DAGE-MTI series PA70) has been found to work remarkably well for low-light, low-contrast environments. To further improve the visualization of the rock matrix and fluid distribution during the micromodel studies, the epifluorescent unit has been acquired and installed.

Rhodamine B (fluorescence dye) was tried; however, the absorption of dye on the rock surface was a problem since it obscures the nonwetting phase within a few hours. Several oil-based fluorescent dyes were tested in a thin slab micromodel. These dyes were found to be only marginally superior to water-based dyes. The oil-based dyes did not absorb as strongly as water-based dyes, but partitioning to the water-phase was a problem. Some of the dyes used were fluoro red, araflus yellow, poly high bright yellow and green, and oil red.

Transformation of an NMR Spectrometer to an NMR Imager

Our preliminary work in this area has been reported (2). The results confirm that the proton NMR peaks of various fluids are broadened considerably when the fluids are contained in the pore spaces of porous rock when very high frequency (270 MHz) is used. Measured line-widths of water in Berea, Cottage Grove, and Cleveland sandstone cores at the NMR frequency of 270 MHz varied from 900 to greater than 4,000 Hz.

To investigate the effect of NMR frequency on the measured line-widths of fluids in porous rock, a Berea core and a Cleveland core each 8 mm diameter and 25 mm long were saturated under vacuum with a 2% NaCl brine in a mixture of heavy water (D_2O) and water. By observing the NMR signal at the proton frequency (270.2 MHz), sodium-23 frequency (71.5 MHz), and deuterium frequency (41.5 MHz) variable frequencies could be observed without having to modify the magnetic field of our NMR spectrometer. The results are shown in table 1. Also included are the measured line-widths in the bulk brine.

A plot of line-width versus frequency for the Cleveland core shows that the line-widths were essentially proportional to the frequency. However, for the Berea core the 23Na and 2D line-widths were considerably larger than an extrapolation from the proton line-width would predict. These two nuclei have nuclear spin of 3/2 and 1, respectively, and therefore possess a quadrupolar moment which leads to line broadening. In bulk solution, rapid tumbling of the nuclei averages out these effects, and a narrow line-width is obtained. In the restricted pore spaces and also from possible adsorption phenomena, the motion of the nuclei would be restricted, and these quadrupolar broadening effects would be enhanced in the case of 23Na and 2D. Because the proton does not possess a quadrupolar moment, this broadening mechanism is not active for protons. Table 1 shows that broadening for protons is higher than for 23Na and 2D at lower frequency even though 23Na and 2D have a quadrupolar broadening effect. Based on these results, a reduction in the magnetic field strength with a proportional decrease in NMR frequency would result in a proportional decrease in line-width.

Table 1. - NMR line-widths of bulk brine and brine in porous rock

Sample	Frequency (Nuclei) 41.5 MHz (2D)	71.5 MHz (23Na)	270.2 MHz (1H)
Bulk brine	1.0 Hz	7.8 Hz	1.5 Hz
Cleveland core	129.0 Hz	248.0 Hz	868.0 Hz
Berea core	967.0 Hz	1585.0 Hz	3286.0 Hz

The new RF coil for the NMR imaging probe was wired into the probe/circuit.

The superconducting magnet for the NMR spectrometer was reduced in field strength to 1.41 Tesla (60.1 MHz) using the magnet power supply on loan from Amoco Production Co. A new radio frequency (RF) coil was constructed to resonate at this frequency and the new coil was wired into the NMR imaging probe circuit.

The pulsed field gradient (PFG) control board was modified to provide switchable frequency selection for multislice imaging. The two new frequency resolution modules for the frequency synthesizer were received and installed. This increases the frequency synthesizer resolution to 100-Hz steps in frequency switching. These modules now allow switchable frequency for multislice imaging.

Software has been written which converts the data obtained from the NMR spectrometer into a format suitable for analysis using the Image-Pro program. The NMR images can be displayed as black and white or false-color images on the CRT and various procedures such as contrast-enhancement or magnification can be employed.

The gradient-refocused echo (GRE) image sequence gave good images of the water phantom and a sandpack (25-30 mesh sand). However, the echo intensity was strongly relaxed by the magnetic gradients, so images of water in sandstone rocks could not be obtained. A spin-echo sequence using a selective 90° pulse and a selective 180° pulse was found to work after proper adjustments on the rephasing gradient pulses. This sequence seems to have some problems developing full signal intensity across the image field with gradients as strong as those used with the GRE sequence. Also, ghost images seem to be more of a problem for fewer than 16 accumulations per step. Discussions with persons experienced in NMRI at the 29th Experimental NMR Spectroscopy Conference in Rochester, New York, indicated that RF coil field inhomogeniety could be part of the problem. The sequence does produce an echo signal of much stronger intensity, and images of water in Cleveland sandstone, a 1,000-md Berea sandstone and a 300-md Berea sandstone were obtained. The image of the 300-md Berea sandstone revealed variations in intensity from visible bedding layers in the sample.

Work is underway to use the imaging process of projection-reconstruction to obtain NMR images. We expect that this technique will give better results on the Berea and Cleveland cores. Software for data conversion is being written to use the available projection-reconstruction programs for image formation.

ACCOMPLISHMENTS

1. Videomicroscopy equipment capable of capturing images of static and dynamic pore-level behavior in thin slab micromodels has been assembled.

2. Pore-cast and thin-slab micromodels have been developed. Etched glass, cryolite, and sandpack micromodels have been fabricated.

3. Displacement experiments (displacement of brine by oil) have been performed in rather uniform cores (Berea) at conditions that provide a viscous dominated flow with unstable front (adverse mobility ratio) to enhance micro-level fluid distribution due to heterogeneities.

4. Field strength of the superconducting magnet of the NMRI equipment has been reduced, and multislice imaging capability for the equipment has been implemented. Software has been written which corrects the data obtained from the NMRI for a format suitable for analysis using the Image-pro program.

5. NMR images of water in Cleveland, 300-md Berea and 1,000-md Berea sandstone cores have been obtained using the spin-echo sequence.

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